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The growth modes of epitaxial Au/Co/Au sandwiches

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Abstract

Optimum growth conditions of epitaxial Au/Co/Au sandwiches with a strong perpendicular magnetic anisotropy have been investigated. The thermally induced evolution of the sandwich morphology, which determines its magnetic properties, was studied by means of reflection high-energy electron diffraction and Auger electron spectroscopy. The roughness of Au and Co surfaces, affected by the sample annealing, was evaluated from the length-dependent variance of topography acquired by atomic force microscopy.

Keywords: Surface roughness; Epitaxy; Gold; Cobalt

1. Introduction

Magnetic properties of surfaces and interfaces have been one of the most important topics in modern magnetism. They have been mostly studied in structures with lowered dimensionality like thin magnetic sandwiches or multilayers. A perpendicular magnetic anisotropy, being of great interest from both basic research and practical applications (e.g. for magnetic storage media) points of view, is one of the results of the presence of interfaces in such structures. Therefore, the Co/Au system has been widely studied since the first announcement of such property in 1986 [1]. The thin Co layer exhibits a magnetisation perpendicular to the film plane, which similarly to other features, such as coercivity, magnetic domain structure, magnetisation reversal and Curie temperature [2–12], is film thickness dependent. Above a certain critical thickness a second order phase transition takes place resulting in the magnetisation reorientation to the in-plane direction.

The earliest studies of these phenomena were based on the assumption that the interfaces were morphologically smooth. However, the existence of interface roughness in real films might affect substantially their magnetic properties. Shape and interface anisotropy is strongly dependent on the film structure and the interface roughness due to appearance of non-compensated magnetic poles. Imperfections of the interfaces may act as pinning centres for domain walls, modifying mechanisms of magnetisation reversal. Therefore, an understanding of a correlation between the film morphology and magnetic properties is of great importance.

In this paper we analyse the growth conditions of Au and Co layers as a function of the type of substrates. On the basis of reflection high-energy electron diffraction (RHEED) and Auger electron spectroscopy (AES) analyses, supported by the topography measurements at various scan sizes, performed by use of atomic force microscopy (AFM), the thermally-induced evolution of the Au/Co/Au sandwich structure is described.

2. Experimental details

The Au/Co/Au sandwiches were grown in a molecular beam epitaxy (MBE) system with the vacuum level in the range of 10^{-10} torr. Glass and sapphire wafers with orientation (11–20) buffered with a Mo layer were used as substrates. Co and Mo were evaporated from electron guns and Au from effusion cells at the rates lower than 0.5 Å/s. All deposition processes were performed at room temperature (RT). The bottom Au layer, 200-Å-thick, was grown either directly on the glass substrate or on the Mo buffer (200 Å) covering a sapphire substrate. The shape of the Co layer was either flat or wedge-like (obtained with the use of a linear motion of the shutter) depending on a specific magnetic measurement purpose. Its thickness range was between 0 and 25 Å. The top Au layer was kept at 80 Å in

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Table 1
Roughness σ and correlation length ξ parameters for Au and Co layers annealed at various temperatures

T (°C)	200-Å Au on glass		200-Å Au on Mo buffer		8-Å Co on Au		15-Å Co on Au	
	σ (nm)	ξ (nm)	σ (nm)	ξ (nm)	σ (nm)	ξ (nm)	σ (nm)	ξ (nm)
RT	4.30	87.1	0.46	64.2	0.18	86.3	0.20	169.2
170	3.75	83.7	0.17	125.0				
200	5.13	121.2	0.19	126.6				
250					0.21	83.3	0.14	138.9
300	6.50	101.3	0.27	124.8				

thickness. The crystalline structure of all grown layers was characterised in situ by RHEED. The AES analysis was carried out to check the chemical composition of the layers and to estimate diffusion processes due to the sample annealing. Ex situ AFM measurements (Nanoscope III) in the Tapping mode were performed for surface roughness investigations.

3. Results and discussion

The growth mode of the bottom Au layer is strongly influenced by the substrate type. Au layers deposited on glass wafers are polycrystalline, whereas the epitaxial growth is obtained for sapphire (11–20) substrates. In the latter case the RHEED pattern exhibits clear streaks for all layers, typical of monocrystalline structure. The Mo buffer deposited on the sapphire substrate has (110) orientation. Such a buffer favours the growth of the Au (111) layer. In spite of a large lattice mismatch, approximately 14%, the Co layer deposited on Au exhibits coherent growth in (0001) orientation. On the basis of our analysis it is impossible to distinguish whether its structure is fcc or hcp type. The top Au layer grows also in the (111) orientation—the same as the bottom Au layer. The following relations between in-plane directions of the constituent layers are found: sapphire (11–20)/Mo(110): [0001]‖[1-1-1], Mo(110)/Au(111): [001]‖[1–10], Au(111)/Co(0001): [1–10]‖[11–20], Co(0001)/Au (111): [11–20]‖[1–10]. The RHEED streaks for Mo ([001], [1–10] and [1–11] directions) and Au surfaces ([1–12] and [1–10] directions) are sharp with distances between them as for the bulk. These layers are relaxed and no strains on their surface are present. In contrast, the Co layer behaves in a different way. The RHEED streaks along [11–20] and [1–100] directions are blurred and the lattice constant, determined from the distance between them, varies with the Co layer thickness. Due to a remained coherence and large lattice mismatch in Co layers grown on Au the existence of expanding strains is observed. Even for 15-Å-thick Co layer the lattice constant is 3% higher than for the bulk. The annealing of Co layers at 250 °C leads to substantial strain relaxation. This phenomenon is discussed further in the paper.

Because of the strong influence of the layer morphology, determined by the growth conditions, on magnetic properties, an unambiguous characterisation of the surface roughness is required. For this purpose the scaling theory for self-affine fractal surfaces was applied [13,14]. The analytic form of a function for roughness analysis is given as:

$$g(R)=2\sigma^2[1-\exp(-(R/\xi)^{2H})]$$

where R is a linear dimension of the analysed area; σ, calculated surface roughness; ξ, correlation length; and H, Hurst dimension. For $R \ll \xi$ the value of the correlation function varies as $g(R) \sim R^{2H}$. Above the correlation length ($R \gg \xi$) the value of the function g no longer scales with R and saturates at $2\sigma^2$. The value of the parameter ξ may be attributed to the linear dimension of islands.

The roughness dependence on the length scale was investigated on the base of the AFM topography measurements. The microscopic images, recorded with the resolution 512×512 pixels, were divided consecutively by 4, 16, 64, 256, 1024 and 4096 non-overlapping square tiles, covering the whole scanned area. The value of $g(R)$ was taken as the mean value calculated over all tiles.

The calculated surface roughness σ and the correlation length ξ are shown in Table 1. As mentioned earlier, the growth mode was determined by the type of substrate. Au layers deposited on a glass substrate are polycrystalline. Typical three-dimensional growth occurs. As a consequence the surface is very rough. Consecutive annealing at temperatures in the range from 170 to 350 °C shows that the roughness has a tendency to increase, similarly to the trend shown by the correlation length, leading to the wider and higher islands of the deposited material.

The quality of the Au layer morphology is substantially improved by using the sapphire substrate buffered with Mo. The deposition at RT results in Stranski–Krastanov mode growth, typical of the (111) plane. Atomically flat islands, approximately 80 nm in diameter, with sixfold symmetry are observed (Fig. 1). The fluctuation of the surface height is of the order of double

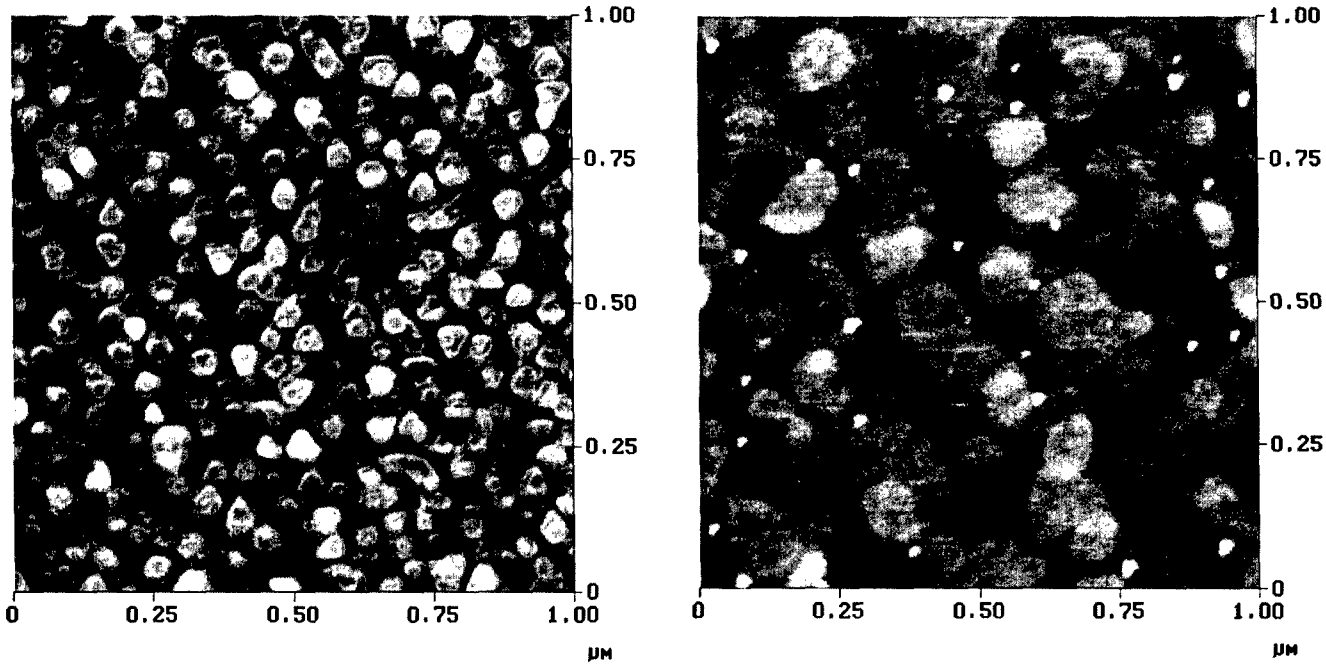

Fig. 1. AFM image of the Au 200-Å-thick layer as-deposited on the Mo buffer (left) and after annealing at 200 °C (right). The range of the grey scale is 2 nm.

(111) plane spacing. Contrary to Au growth on glass, the vacuum annealing of the Au layer deposited on the Mo buffer improves significantly its morphology. The temperature of 170 °C is high enough to reduce the roughness more than twice (fluctuation of the surface height is suppressed to single monolayer step height) and increase the diameter of atomically flat islands by the same factor. The annealing at higher temperatures up to 600 °C does not affect the topography markedly. It is worth to mention that even a small miscut of a sapphire wafer might change the growth of the Au bottom layer from the island-like to terrace-like mode.

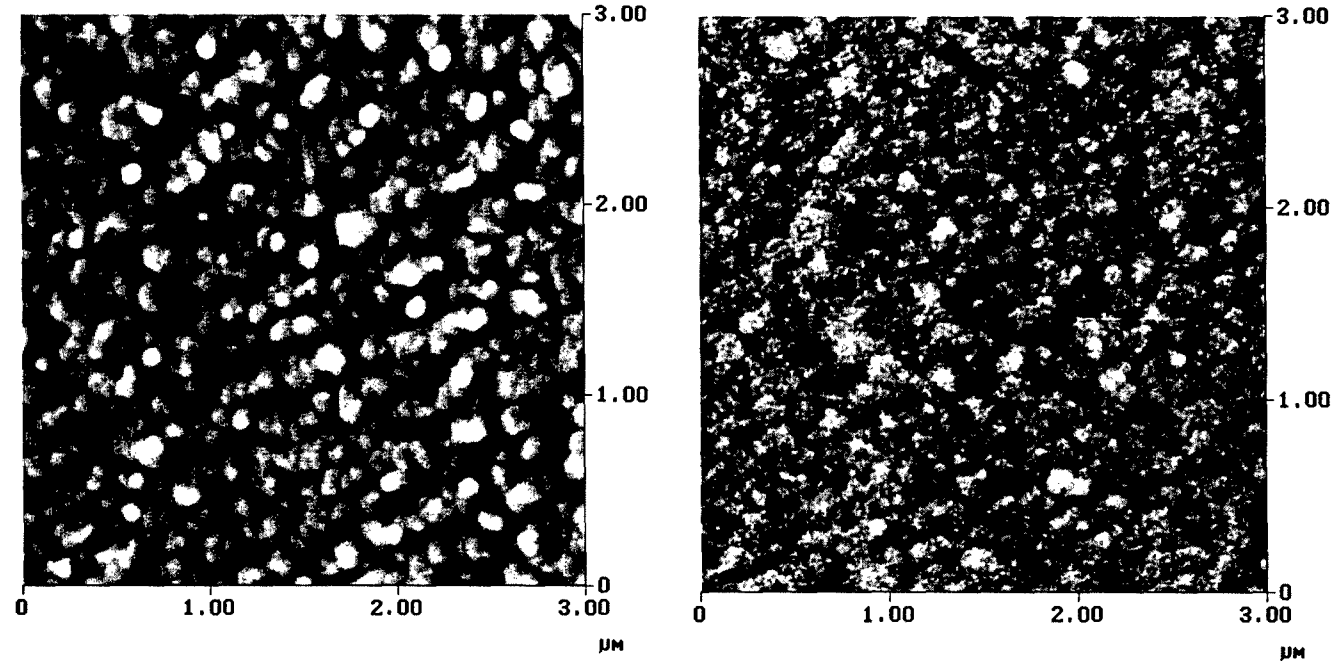

Fig. 2. AFM image of the Co 15-Å-thick layer as-deposited on the Au layer (left) and after annealing at 250 °C (right). The range of the grey scale is 4 nm.

Fig. 3. RHEED streaks acquired on as-deposited (left) and after annealing at 250 °C (right) 8-Å-thick Co layers. Before annealing streaks are blurred, but single and correspond to the lattice constant 2.72 Å. After annealing they are split revealing the lattice parameter 2.59 Å and 2.83 Å for outer and inner, respectively.

The evaporation of Co layers was performed at RT on the bottom Au layer, previously annealed at 200 °C. The surface of the as-deposited Co layer has the island-like structure, similar to that for the annealed Au layer (Fig. 2). Additionally, a weak structure of the island surface is visible in the AFM image. The Co surface roughness is comparable to that of the annealed Au layers, but the correlation length takes different values as the Co layer thickness changes. For an 8-Å-thick Co film the parameter ξ oscillates around 90 nm, whereas for a thicker layer (15 Å) it increases up to 170 nm. Annealing at 250 °C for 45 min causes smearing of the surface island structure. Their contours, although still visible in the AFM image, are much less pronounced. The annealing process does not affect markedly the roughness of the thin Co layer whereas for the thicker one it results in the surface smoothening as reported in Speckmann et al. [4].

The RHEED pattern observation allows to investigate the existence of strains due to the lattice mismatch of both components of the sandwich. The surface lattice parameter of the as-deposited 8-Å Co layer is substantially enhanced up to the value of 2.72 Å, in comparison to 2.51 Å for the bulk. In a 15-Å-thick Co layer the strain relaxation is stronger, revealing the value of 2.59 Å. Annealing of the Co layer performed at 250 °C evidently affects its crystalline structure. For an 8-Å-thick Co film the splitting of the RHEED streaks occurs (Fig. 3), being a proof of the lattice constant relaxation to the values of 2.54 Å and 2.84 Å for Co and Au, respectively. Surprisingly, such splitting is not observed for 15-Å Co layers. For this sample the lattice parameter after annealing, measured by the distance between the RHEED streaks, is equal to 2.83 Å—very close to the Au bulk value (2.88 Å). On the basis of AES spectra comparison from both as-deposited and annealed 15-Å Co layers, it is evident that Au behaves as a surfactant giving rise to an increase of the AES signal for Au and a suppression of the respective signal for Co.

Since Au and Co are mutually insoluble, the reverse diffusion may take place after the annealing. Most probably, due to the diffusion activated by annealing, a non-continuous Au film appears on the surface of the thin Co layer, whereas in the case of the thick Co film, it is fully covered with Au. Moreover the coherence between Au and Co layers is lost, giving rise to the relaxation of strains. This is compatible with the evolution of Co surface morphology, monitored changes in the RHEED pattern and the Auger electron spectrum after the annealing of the samples. Thus it is reasonable to expect that the annealing lowers substantially magnetoelastic contribution to the magnetic properties of Co layers. Magneto-optical measurements are in progress and will be published soon.

4. Conclusions

The sapphire substrate buffered with Mo is ideal for growth of smooth Au/Co/Au sandwiches. The annealing above 170 °C improves the flatness of the Au surface—atomically smooth areas of a few hundred nanometers in diameter occur. In the as-deposited Co layers the expanding strains should result in the significant magnetoelastic contribution to magnetic properties. The thermal treatment releases strains and the lattice parameter relaxes. The Au acts as a surfactant appearing on the top of the Co layer after annealing at 250 °C.

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